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The Robotic Building Construction System

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Abstract. The application of that robot system for the automatic assembly of commercial cavity blocks is the subject of the following report. The entirely different characteristics and abilities of assembly robots are not taken into consideration. However, their dimensional tolerance is relatively small (0.5 mm). Furthermore as cavity bricks, they have conic and oval recesses. Both features are strongly favourable for automation.
This report will highlight specific problems during automized construction assembly with commercial standard assembly elements, and help to solve them[6].

1. The robot system used

For the assembly of cavity blocks a gantry robot system was used. That robot system has been depicted in detail in the report "Experiences with the Construction of a Building Assembly Robot" [2].

2. The gripper system

2.1 Requirements

Task sharing between robot and gripper system. The partial system "gripper" initiates directly the interaction of the robot system with the assembly element. The hand axes used for the positioning of the TCP have to be related to the robot. Grippers can, however, dispose of "finger axes" of their own, which have no influence on the position of the TCP.
Robot grippers are usually special constructions to do one or several tasks. For building assembly, a gripper can be constructed not only for the free and unimpeded grabbing and placing of blocks. It must be able to handle further assembly situations which are mostly characterized by a limited working space. In the depalletizing process, the grabbing of the blocks is impeded at least on two block sides by adjoining blocks. Likewise, when the blocks are put down, it cannot be taken for granted that its sides are free [1], [10], [17] (see chapt. 2.2 and 8).
Gripper types. Due to the design of the gripper it is possible that depending on the assembly element 1. the positions of robot and assembly element remain uninfluenced, 2. the gripper adjusts to the position of the assembly element or 3. the assembly element adjusts to the position of the gripper during the grabbing process (fig.1).

Adjustment	Type of gripper	Type of assembly element	Example
1. none	Point gripper	independent	Sucking gripper
2. Gripper on assembly element	compliant gripper	independent	mech. flexibility
3. Assembly element on gripper	independent	compliant element	conic gripping areas
4. Robot on assembly element	independent	independent	Sensor guidance

Fig.1. Table of gripper types

The fourth possibility that the robot adjusts to the position of the assembly elements is independent from the gripper system (see chapter 4, Characteristics of robot oriented building block system).

Compliance. In building systems, compliance refers to the ability to passively offset errors in position and orientation of the blocks and block connections to the robot [12], [18]. Positioning errors of the robot cannot be offset by the 'gripper/block' system. Probably the easiest and thus most robust and cheapest possibility of correcting the postion of the blocks and the orientation to the robot are mechanic offsetting elements. Responsible for this compliance is not only the design of the gripper, but of the overall system 'gripper - block'. The cavity blocks show features of design, such as cone or cylinder forms on the possible gripping areas, which foster compliance (see chapt. 4.2 and 4.4).

Point and cone - adjusting and non-adjusting grippers. Depending on if the assembly elements are to adjust in their position to the gripper, point or cone grippers can be employed. The terms 'point' and 'cone' are used here in a very general sense as synonyms of 'adjusting' and 'non-adjusting'.

In a mechanic realization with point grippers, a contact between gripper and assembly element at three points is sufficient to "hold" it clearly. In fact, the same could be achieved with a non-mechanic (e.g. magnetic) principle. In particular the wide-spread vacuum grippers are point grippers in the sense of the definition. If, however, the position of the element was uncertain prior to the grabbing process, it will also be undefined afterwards. However, if the gripper, the assembly element or both have compliant structures (e.g. two opposite conic gripping areas), a centering of the assembly element during the grabbing process can be forced.

Strictly speaking, those are two unfeasible extreme forms of grabbing with and without geometric adjustment of the gripper/block system. In reality, every gripper is somewhere in between and can only approximately fulfil one of the two forms.

2.2 Gripper constructions realized and used

Physical principles of interaction. There are quite a number of possiblities and mechanisms to lift and hold a block.

Gripping areas	Form	Contact with cylindrical areas
		Contact with conic areas
		Contact with even areas
	Type	Areal contact
		Point contact
	Position	grab from outside
		grab from inside
Mechanics		Scissor gripper, eccenter, parallel jaw gripper, bellows, bent lever
Actuation		Hydraulic, Pneumatic, Electric

Fig 2. Suggested solutions for gripper constructions

Physical principles are force jointing (flow pressure, frictional force, magnetic force, etc),

Charac-teristics	Scissor gripper	Parallel gripper
Compliance in gripping direction	The compliance alongside the gripping direction is achieved via scissor mechanics. It can be supported by tapered jaws, if their parallel positioning is forced by corresponding mechanics (parallelogramm).	The compliance alongside the gripping dircection is achieved via an adjusting cable line. It can be supported easily by tapered jaws.
Compliance cross-gripping direction	It can also be achieved by tapered jaws, if their parallel positiong is forced by corresponding mechanics (parallelogramm).	It can easily be achieved by tapered jaws.
Grabability	Only from inside	From outside and inside
gripping width	The feasible gripping width is limited by the servo principle, the contact pressure of the pneumatic cylinders and the coefficient of friction of the combination of working materials.	The feasible gripping width is determined by the stroke of pneumatic cylinders.

Compactness and maneuverability	Due to the minor measurements, the blocks can also be positioned in special assembly situations (e. g. abutting), without building parts jutting above the grabbed block impairing the gripper [4].	Due to the requirement that larger blocks may also be grabbed from the outside, the parallel gripper usually builds on a larger scale than a pure inside gripper and generally stands out over the block.
Gripper stroke - grab around obstacle	The scissor gripper can only grab from inside and needs a space between the two gripping areas which is freely accessible. Consequently, due to its kinematics it is unfit to grab around obstacles. Its stroke length must only be adjusted to the largest and the smallest gripping width necessary. Thus it can be employed with as large a stroke as desired.	The parallel gripper is in a position to grab around obstacles. The stroke length must be chosen in such a way that the closing as well as the opening for all necessary grabs is possible without collision (see fig. 17)
Vertical compliance	A vertical compliance can be achieved with paralled jaws, if their parallel positioning is forced by corresponding mechanics (parallelogramm).	This gripper is especially characterized by its compliance in vertical direction. If a block is positioned too far in vertical direction, the jaws slide on without damaging the block or the robot.
Number of blocks which can be grabbed at once	As a pure inside gripper it can only grab one block at a time.	Two blocks can be grabbed at one time.

Fig 3. Comparison of scissor and parallel gripper

geometrically-positive jointing (hooks, screws, etc.) and composition of matter (bonding agent, etc.). Some alternative solutions suggested for gripper constructions are listed in fig. 2.

For assembly experiments a gripper with scissor mechanics was available. In addition, a parallel jaw gripper was constructed (fig.3). Those two kinematics probably represent the most reasonable possibilities [1], [4], [10].

2.3 Study of different gripping variations and gripping constellations

2.3.1 Interaction of gripping kinematics, jaw form, stroke and stroke position

In this chapter the different possibilities of grabbing a block are examined, in view of the development of a gripper ideal for the GISOTON cavity block system (see chapt. 4.4). Hereby gripping kinematics, jaw form and stroke or stroke position are varied. The results of the theoretical study are demonstrated in the form of a table (fig. 4) and complemented by means of practical tests [17]. As very different assembly situations are encountered during a building assembly procedure (see fig. 6) and unnecessary gripper changes want to be avoided, we are looking for the mechanism and jaw form with the greatest variety of gripping possiblities able to grab every block at least in one sensible way.

Gripping kinematics	Jaw form	Gripper	B	T	H	i	a	I	A
Scissor gripper	Point	1	50	12	190		110		300
	Cylinder	2	83	21	190		128		318
Parallel jaw gripper	Point	3	50	50	320	0	100	320	420
		4				10	110	330	430
		5				30	130	350	450
		6				70	170	390	490
	Cylinder	7	83	42	320	0	84	320	404
		8				10	94	330	414
		9				30	114	350	434
		10				70	154	390	474
	Cone	11	83	10	320	0	20	320	340
		12				10	30	330	350
		13				30	50	350	370
		14				70	90	390	410
	cyl./con.	15	83	30	320	0	60	320	380
		16				10	70	330	390
		17				30	90	350	410
		18				70	130	390	450

i [mm]	Jaw insides - distance in closed stage - indicates the geometric position of the gripping stroke
a [mm]	Jaw outsides - distance in closed stage
I [mm]	Jaw insides- distance in opened stage
A [mm]	Jaw outsides - distance in opened stage
B [mm]	Jaw width (cross-gripping direction)
T [mm]	Jaw depth (alongside the gripping direction)
H [mm]	Stroke of gripper
G [mm]	Gripping width - indicates the distance of the respective gripping areas to one another. It varies accordingto the individual grab.
R [mm]	Gripping space - it refers to the space a gripper has at its disposal to put down a block, without effecting a collision with other assembly elements or the subsequent displacement of that block. The *gripping space* is calculated in such a way that the gripper is not impeded in the gripping process nor while letting go off the block by the block itself. It is to decrease, possibly, depending on the assembly situation (e.g. abutting).

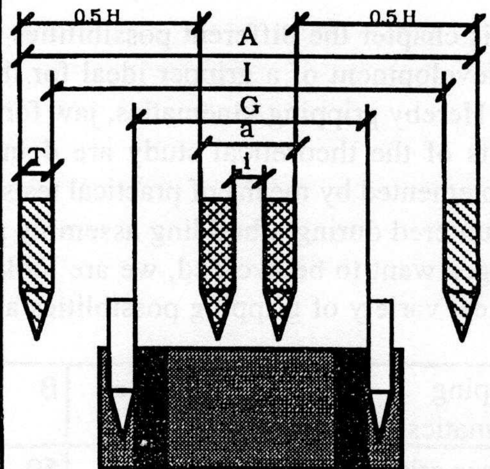


Fig.4. Measurements of different grippers

Definition of the grippers (gripper constellations) analyzed.

They differ regarding gripping kinematics, jaw form and stroke (see fig. 4).

Gripping kinematics. A parallel jaw gripper and a scissor gripper are available (fig.4).

Gripper jaws. All gripping kinematics can be equipped with different gripper jaws (fig.5).

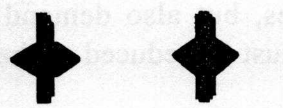
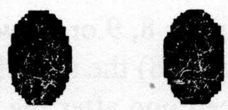
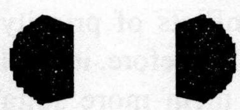
Type	Cross-section of jaws	Description	Explanation
Point		Point gripper with two superposed ends which prevent a side-turn of the block	Point-shaped grabbing from inside and outside
Cylinder		Cylindric gripping areas on jaw insides and outside.	Compliant grabbing on the cylindric block insides, part-compliant grabbing on the conic block outsides
Cone		Cone form on the jaw insides, rounded inner edges	Compliant grabbing on the conic block outsides (grabbing is only possible from the outside)
Cylinder /cone		Cylindric gripping areas on jaw outside, conic gripping areas inside, rounded inner edges	Compliant grabbing on block insides *and* block outsides.

Fig. 5. Jaw forms used

Gripping stroke. Both grippers can only be open or closed, they cannot adopt an in between-position without grabbing an object.

As these blocks offer quite a number of grabbing possibilities, in which the distance of the gripping areas to one another varies strongly, an employment of as many different grabbing possibilities with one and the same gripper requires a large gripping stroke. Often however gripping kinematics with jaws closing too tightly or open too widely represent a problem - before the grabbing or when the block is put down - resulting in the collision with other points of the same block or with other assembly elements. For this reason the length of the gripping stroke and its geometric position must be carefully adjusted to the requirements of the different grabs (fig.6).

Geometric position of the ripping stroke. The difficulty of the different gripping stroke and their geometric position (see fig.6) required for different grabs results from the ability of the parallel gripper to "grab around" obstacles, but its inability to adopt more than two stages.

The gripping areas of the block. Right from the beginning the number of gripping area can be reduced by the charging space of the block, as it is obviously impossible to grab there [1]. For the same reasons the considerations of gripping possibilities on the Y, Z planes of the blocks is superfluous.

2.3.2 Valuation of the grabbing possibilities for the cavity blocks

The grabbing variations listed differ considerably with respect to their compliance and their symmetry. It has been the objective to develop a gripping system which on one

hand offer the highest possible compliance, but at the same time would be capable to handle all assembly situations (fig. 8).
As the blocks used offer numerous grabbing possibilities, but also demand quite different qualities from the gripper, the number of grabs must be reduced to the most useful, for which a corresponding gripper is developed.

2.3.3 Valuation of gripper constellations

Consequently, for the grabs recommended, gripper constellations 7, 8, 9 or 18 would be most suitable (see fig. 4). As in ordinary construction (W3 - see fig.8) the most frequent assembly situation requires that normal blocks are simply placed one after the other, a good grab for that needs to be found. In the assembly tests, a relatively complicated corner was constructed, which therefore contained a lot of special blocks [17]. In spite of that, only 13 special blocks with altogether 49 bricked blocks. Most suitable for normal blocks is gripper 18 (see fig. 4) as a gripper with a large gripping width and cylindric-conic jaws, because the highest compliance can be achieved with it.
These geometric observations show that time and again conflicts of priority in the development of grippers for different grabbing methods appear. Therefore, it would make a lot more sense to design blocks in a way which makes them more suitable for automation, although among the commercial elements they do belong to the blocks most usefully designed for automation (see chapt. 4).
Normal blocks. In order to grab a normal block for a usual assembly situation (W1, W2, W3 - fig.19), the versions 1 and 21 are suitable due to their high compliance. In this case, grab 1 is the better of the two, because it uses the cone and because it uses the gripping areas which are further on the outside. If a normal block is to be abutted, variations 2 and 3 are most suitable, because they are very compliant owing to the cone form of the gripping areas and they use gripping areas which are far apart. It would also be conceivable to use grabs 22 and 23 (fig.6), but they have a lower compliance and are furthermore strongly asymmetric.
Special blocks. In order to place special blocks, grab 24 is the most appropriate. It is relatively well compliant and does not lead to collisions, when the block is put down. If the block is put down separately, grab 9 is more suitable due to its higher compliance. The most difficult situation is probably the abutting of special blocks. Grabs 10 and 11 (fig. 6) are most appropriate here. However, they are not suitable for grippers with a great stroke. In that case, variations 18 and 31 must be employed.

3. Conveyance of assembly elements

The different methods of conveyance are classified according to the requirements they have with respect to a robot system (see chapt. 4).
Individual conveyance. For a robot, it is probably the most convenient, if it can pick up every block, no matter if normal or special, at exactly the same point in a clearly-defined position. This conveyance is conceivable by means of conveyor belts or sliding. In that case an image processing system or other sensor system would be superfluous. However, the problem of depalletizing is transfered into the stage before

automized assembly. Obviously, it there creates an increased demand for personnel or machinery, because the blocks have to be moved from the pallet on which they are usually delivered, and placed individually in a certain, defined order (normal blocks, special blocks). This type of block conveyance is appropriate, if the blocks cannot be provided on pallets, for example because the robot functions in a closed building. Then, conveyance by means of a belt through door or window openings would be conceivable.

Individual conveyance divided into normal and special blocks. This is the second easiest solution for a robot. What is problematic here again is the depalletizing procedure because it is causes additional effort before assembly. This effort can be reduced if normal and special blocks are delivered on separate pallets. It is further reduced because now the blocks no longer need to be placed in a certain order. A negative factor is that more room is needed for conveyance on separate belts.

Separate pallets for normal and special blocks. The producers palletize the blocks automatically, so that depending on block dimension and producer they are always delivered in the same order, which makes the emploment of depalletizing programs possible. During transport or unpacking of block packages, dislocations of the blocks take place, in particular if the packages are only tied together with belts [10]. If an image processing system or other sensor system is to be done without, the position of each block must be exactly defined. This may be done by placing the pallet according to exact definitions and by a readjustment of the blocks after transport. These processes have to be supported by compliant grippers (see fig.6). This type of conveyance is advantageous, if enough room is available for several pallets, if the room is freely accessible (so that the pallets can be positioned with a crane, for example) and if the working space of the robot is large enough for him to be able to remove the blocks from the pallets.

Same pallet. This method is the most demanding for a robot system. An image processing system is now inevitable, in order to differentiate the different blocks and to recognize their position. If an image processing system is used, neither blocks nor pallets need to be exactly positioned. The robot must now be in a position to change the block order if necessary. The depalletizing problem is now entirely within the field of automized construction assembly.

4. The assembly process

4.1 Possible assembly situations

Nr.	Building part	Assembly situation	Condition	Example
W1	Wall	Free positioning of blocks (no contact)	placing on foundation	
W2			placing on other blocks	
W3		Positioning of one block next to other		
W4		Junction with existing building part	abutting alongside the block	Two-leaf block-work
W5			abutting cross-block	Interior walls
W6		Walls with different block dimensions	placing of blocks with flexible lengths	
W7		Closure of a gap in field		
W8		Closure of a gap in existing building part	abutting into gap	
E1	Corner	End junction at bricked corner		
E2		Side junction at bricked corner	toothing	
E3		Walls with different block dimensions	placing of blocks with flexible length	
E4		Closure of a gap at the corner with side junction		
E5		Closure of a gap at the corner with side junction		
D1	Ceiling	Bricking below an obstacle	one or two-dimensional insertion from the side	Room ceiling (or toothing of interior walls)
D2		Insertion of closer block below an obstacle	one-dimensional insertion from the side	
D3		Bricking of corner below an obstacle		

Fig 6. Assembly situations

4.2 Jointing techniques

4.2.1 Horizontal jointing

Horizontal positioning. The position of the actuator (gripper) represents the controlled dimension in this process. The jointing forces must be limited mechanically or by a control system, in order to prevent damage of the robot or objects in the working area. This may be done by sensors or mechanic flexibilities. Grippers which are flexible when clearly-defined limits of horizontal or vertical jointing forces are exceeded can be named as examples of special constructions. Hereby, the force sensors are replaced by a type of preset breaking point. This can be done by pneumatic grippers, which give way flexibly when a certain pressure limit is exceeded by parallel jaws which simply slide through when the jointing forces are exceeded. Of course, these flexibilities have geometric limits; they must at least be large enough to balance the tolerance of positioning accuracy.

Absolute positioning. Every block positioning depends on an absolute world coordinate system, the absolute zero position of which was defined prior to the assembly process. The blocks are placed on their nominal positions, which are then defined as the distance to this zero postion. A balance of measuring deviations of blocks and positioning inaccuracies is achieved automatically by different joint widths. The joint width, which is theoretically constant in the case of very dimensionally-accurate block systems, must in advance be calculated in such a way that it can offset any measuring tolerances [10].

Relative positioning. The position of the previous block is determined by a sensor system and the block placed in the nominal joint distance. The positioning accuracies of the robot and the measuring system are only relevant for the first block in a row [10]. Depending on how the distance to the previous block is registered, a control of jointing forces may not be necessary. An advantage of relative positioning is the fact that the acceptable joint width can be preset and thus a steady joint width can be obtained. A drawback is that errors of position and measurement are in part systematical and thus add up, to the effect that eventually a number of major errors occur, which have to be offset. An average measuring deviation of just 1 [mm] leads to a deviation of up to 40 [mm], if a 10[m] long wall with a block length of 250 [mm] is assumed. This can be offset by cutting the last block of a row accordingly or by positioning the last block at the end and filling of the resulting gap with mortar. An automatic measuring of the remaining block length and the specific cutting of the last block requires a high technical effort and large machinery, so that this method is not suitable for automation on a construction site. A stockage of blocks of different lengths is not possible due to the large amount of blocks needed [1], [10], [17].

Non-bonded jointing. The jointing forces are the controlling factor of this method. The block to be positioned is pressed against the previous block with a controlled force. The position of the actuator must be registered by sensors and limited, so that - if a previous block is missing or if the robot has mispositioned the block - the robot does not move on until it meets with an obstacle.

4.2.2 Vertical Jointing

Vertical positioning. (see horizontal jointing - chapt. 4.2.1).
Absolute positioning. Just as in the case of horizontal abolute positioning, every block positioning depends on an absolute world coordinate system. The balance of the measuring deviation of the blocks and the positioning inaccuracies can only be effected automatically, if the positioning is done into a thick mortar underbed.
It is impossible with dry blockwork , as the blocks are placed directly one on top of the other. In this case a limitation of the vertical jointing forces is necessary. This can be realized e.g. by mecanical flexibilities. This includes parallel gripping jaws which simply slide through after exceeding the static friction between gripper and stone. An advantage of this method is the fact that the controlled jointing force displaces or crushes small pieces of dirt between the blocks which may provoke positional errors in the force-free jointing process.
Relative positioning. What is true for horizontal, relative positioning is basically true for the vertical superposition of building elements (see chapt. 4.2.1). The desired joint width must be filled with mortar.
Non-bonded jointing. As in the case of horizontal jointing, the block to be positioned is pressed against the previous block with a controlled force. But due to the fact that in vertical direction blocks are supported by the foundation the risk of displacement is reduced.

4.2.3 Jointing techniques of absolute positioning

One-dimensional	Two-dimensional	Three-dimensional
This jointing process is necessary if the working area is limited in vertical and horizontal direction. That happens e.g. if finishing block of an interior wall must be placed below the ceiling. What is extremely problematic in that case is owing to the major limitation of the gripping areas.	This is probably the most frequent jointing process. In general the robot first takes a intermediate position on the level of the wall which is to be built and only then places the block two-dimensionally into its final end position (see chapt. 4, fig. 1). The result is that the block meets with other assembly elements in vertical and horizontal direction at the same time only towards the end of the jointing operation, when the actual end position has for the most part been reached. An early friction with other elements and a canting in extreme cases is thus prevented.	If a block needs to be placed in three directions against other elements, as is the case if a gap with following bricks on the sides needs to be closed, three - dimenional positioning is necessary. This is required, just as with two-dimensional jointing, so that there is no early friction or canting.

Fig.7. Jointing techniques of absolute positioning

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